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SYMBOLS

C	specific heat, J/g °C
d	slab thickness, cm
F	dimensionless time parameter, $\frac{\alpha t}{d^2}$
k	thermal conductivity, W/cm °C
Q	absorbed heat flux, kW/cm^2
S	thermocouple sensitivity at given temperature, mV/°C
T'	temperature rise above ambient, °C
T_M'	melting temperature above ambient, °C
t	time from application of heat flux, sec
X	relative depth into slab, X = 0 front, X = 1 back surface
α	thermal diffusivity, cm^2/sec
ρ	density, g/cm^3

CALORIMETER PROBES FOR MEASURING HIGH THERMAL FLUX

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SUMMARY

Expendable, slug-type calorimeter probes have been developed for measuring high heat-flux levels of 10-30 kW/cm^2 in electric-arc jet facilities. The probes are constructed with thin tungsten caps mounted on Teflon bodies. The temperature of the back surface of the tungsten cap is measured, and its time rate of change gives the steady-state, absorbed heat flux as the calorimeter probe heats to destruction when inserted into the arc jet. Design, construction, test, and performance data are presented.

INTRODUCTION

Expendable, slug-type calorimeter probes have been developed for measuring the extremely high heat fluxes in arc jet facilities used for simulating heating conditions during planetary entry. A tungsten cap is utilized for its high melting temperature as a calorimeter slug. The slope of the temperature vs time curve of the back surface of the cap indicates the absorbed steady-state heat flux as the probe heats to destruction.

The high heat-flux levels to be measured are beyond what can be withstood by cooled, steady-state calorimeters. Another type of calorimeter, the null-point or gradient calorimeter, could be used by sweeping it through the arc jet for a flyby indication of the heat flux and thus avoid being destroyed (ref. 1). In the gradient or null-point calorimeter one or more thermocouples are imbedded in a thick slab to measure either temperature gradients or the approximate mean temperature of the slab to deduce transient, time-varying heat flux by means of inverse heat-transfer analysis. A fundamental problem with using a transient calorimeter in this application, however, is the presence of a large, high-frequency-induced noise signal from the arc jet resulting from the proximity of the arc jet's cathode to the calorimeter probe. With a slug-type calorimeter that can withstand a longer exposure time at these high heat-flux levels, a low-pass filter can be used to greatly reduce the electrical noise interference.

The complexity of the construction and data reduction required for imbedded thermocouple calorimeters also discourages their use by this method. The tungsten cap calorimeter with a single thermocouple located at its back surface is relatively easily constructed and is expendable for each application.

The use of tungsten with its high melting temperature results in a slug-type calorimeter that attains the steady-state condition of a linear temperature slope long enough to be measured before front surface of the calorimeter melts. For a 1-mm-thick tungsten cap, the time of linear temperature slope prior to melting is on the order of 40 ms at flux levels of 20 kW/cm^2. By using the linear portion of the calorimeter's response, one can apply the simple calorimetric heat-balance equation with known material parameters to calculate heat-flux measurements above the level of 10 kW/cm^2 where calibration facilities are not generally available.

The efforts of William Carlson, Warren Winovich, and George Liu in the design and testing of these calorimeters are gratefully acknowledged.

DESIGN AND CONSTRUCTION

A drawing of a typical calorimeter probe is shown in figure 1. The probe consists of a cap, body, and thermocouple assembly. The calorimeter cap is machined from wrought, sintered tungsten and is attached to a Teflon body by two steel pins. Copper has also been used for the cap, but the high melting temperature of tungsten allows for more than double the linear response time.

The cap has a blunt shape like the test models that are used in the facility, which enhances the radiative heating from the shock layer ahead of the probe. A slight curvature ensures that the stagnation point of the arc jet flow will be near the center of the probe rather than near the edge if the probe is not aligned perfectly normal to the flow. The cap diameter is sized according to the desired blockage for a given arc jet nozzle. The typical cap diameter is 4.1 cm and 1 mm thick. Probes have been constructed with diameters of 2.0-5.5 cm and thicknesses of 0.5-2.5 mm. The thickness is optimized for the heat-flux level as will be explained.

The Teflon body is drilled to accommodate the thermocouple, which is pressed against the back surface of the cap by a spring-loaded ceramic holder. The thermocouple junction is flattened to provide uniform contact area, and the spring force is set for approximately 48.3 N/mm^2 (7000 $lb/in.^2$). This method of attaching the thermocouple was found to be more reliable than spot welding. A robust probe construction is required to withstand the acceleration forces and thermal shock resulting from the rapid insertion of the probes into the arc jet flow. The thermocouple typically used is chromel-alumel, although platinum thermocouples have been used for higher heat fluxes when the back surface temperature may exceed the thermal limit of chromel-alumel.

ANALYSIS

The rapid insertion of the calorimeter probe and the uniform heat flux over its large diameter-to-thickness ratio cap allows one-dimensional heat transfer analysis to be used. The familiar equation for the temperature rise of a semi-infinite slab as a function of time and distance through the slab after application of a step input of heat flux is given by equation 1 (ref. 2).

$$T' = \frac{Qd}{k}\left[F + \left(\frac{1}{3} - X + \frac{X^2}{2}\right) - \frac{2}{\pi}\sum \frac{(-1)^n}{n^2} e^{-n^2\pi^2 F} \cos n\pi X\right] \quad (1)$$

This equation is plotted in figure 2 for front and back surface temperatures. The curves illustrate the surface temperature rise as a function of absorbed heat flux and exposure time. The useful region of the curves for steady-state analysis of a probe used as a slope calorimeter is the linear portion of the back surface curve up to the time when the front surface curve reaches the melting temperature. The linear slope portion starts at the time when the dimensionless time parameter or Fourier number F exceeds 0.4. Above this value, the transient series term of equation 1 becomes insignificant. The time derivative then gives the simple, steady-state calorimetric heat balance equation in terms of the temperature slope.

$$Q = d\rho C \frac{dT'}{dt} \quad (2)$$

and in terms of the observed thermocouple voltage slope it is

$$Q = \frac{d\rho C}{S} \frac{dV}{dt} \quad (3)$$

This lumped parameter equation is used with constant coefficients C, k, and S. The variation of these values with temperature is minimized by selecting mean values for the temperature range corresponding to the linear slope region.

The usable steady-state, linear slope response can be calculated from the steady-state portion of equation 1. The time to melt is given by

$$t_M = \frac{T'_M d\rho C}{Q} - 0.33 \frac{d^2}{\alpha} \quad (4)$$

The time to the steady-state, linear response from the Fourier number is

$$t_L = \frac{Fd^2}{\alpha} = \frac{0.4\ d^2}{\alpha} \quad (5)$$

The time of linear response is the difference

$$\Delta t_L = t_M - t_L = \frac{T'_M d\rho C}{Q} - \frac{0.73\ d^2}{\alpha} \quad (6)$$

This desired response time may be maximized with respect to the slab thickness for a given material and heat flux by differentiating and solving for d:

$$d_{max} = \frac{T'_M k}{1.46\ Q} \quad (7)$$

Table 1 gives the parameter values selected for tungsten and copper caps, and table 2 gives the cap thicknesses for the maximum time of linear response for several heat-flux levels.

TESTING

A heat-flux source suitable for testing and calibration of calorimeters at levels of 10 kW/cm^2 was not available. Conventional sources can produce heat fluxes up to about 1 kW/cm^2. A calibration test source also requires a uniform heat flux over at least 1 cm^2 to minimize radial conduction effects and a shutter control to provide for a fast-rise heating pulse.

For testing the calorimeters, the heat flux source primarily used was a high-intensity radiation source similar to that described in reference 3. It consisted of a high-pressure xenon-arc lamp in an ellipsoidal reflector with an optical integrator and a high-speed shutter. Heat fluxes up to 1 kW/cm^2 were used and had a uniformity variation of 15% over 1 cm^2.

The tungsten slope calorimeters were exposed to a 0.2-sec heat pulse and their slope responses recorded. From equation 3 the absorbed heat flux was calculated using parameter values for the average temperature range. Comparison of the measured flux values to secondary reference calorimeters provided a relative calibration. The reference detectors included a cavity radiometer and several commercial Gardon-type calorimeters. The accuracy of the reference calorimeters was approximately 15%, including absorptivity effects.

The measured heat-flux values were typically 70-85% of the reference calorimeter values. This reduction is attributed to thermal contact losses of the spring-loaded thermocouples. The relative calibration values measured at low-heat fluxes are not extrapolative to heat fluxes of a factor of approximately 20-fold or higher, but are used for testing the calorimeters for defects and relative uniformity of response.

PERFORMANCE

The tungsten cap calorimeters have been used in the Giant Planet Pilot Facility (ref. 4). This facility is a 100 MW arc heater capable of producing heating rates up to 30 kW/cm^2. Tests with the calorimeters have been made at powers to 25 kW/cm^2. Both radiative and convective heating occurs, with radiative heating predominating at higher powers for blunt-nosed calorimeters.

The calorimeter is mounted at the end of a swing-arm sting, which positions it in the arc jet flow, and a sabot covering the calorimeter is released by the flow resulting in an exposure rise time of less than 10 msec. The thermocouple signal is recorded on a high-speed oscillograph after passing through a low-pass filter and light-coupled isolation amplifier. The filter reduces noise induced by the arc, and the amplifier provides gain and high-voltage isolation.

A typical run record is shown in figure 3. The thermocouple response has a linear response occurring from about 20 ms after the start of insertion of the probe to about 40 ms after insertion, when the onset of melting of the tungsten cap and thermocouple occurs. This calorimeter had a 4-cm diameter tungsten cap 1-mm thick with a chromel-alumel thermocouple. The linear slope of the response indicates an absorbed heat flux of 14 kW/cm^2. The incident heat flux would be approximately 35% higher after corrections are applied for the radiative component of the heat flux and the absorptivity of the calorimeter. The radiative component is determined from independent radiometer measurements, and the absorptance of the tungsten cap surface has been measured to be approximately 75%.

CONCLUSION

Tungsten cap calorimeters with diameters from 2-5 cm have been developed and used to measure arc jet heat fluxes up to 30 kW/cm^2. Their relatively simple construction allows them to be expendable and heated to destruction to obtain a measurable temperature slope at high heating rates. Absorbed heat fluxes can be calculated directly from the temperature slopes by using selected material parameters of the calorimeters.

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TABLE 1.- CALCULATION VALUES

Material	Parameters at 1000 °C				
	T_M, °C	ρ, g/cm^3	C, J/g °C	k, W/cm °C	α, cm^2/sec
Tungsten	3410	19.2	0.16	1.13	0.37
Copper	1083	8.93	.475	3.5	.83

TABLE 2.- THICKNESS FOR MAXIMUM TIME OF LINEAR RESPONSE

Absorbed power Q, kW	Tungsten		Copper	
	d_{max}, cm	Δt_L, sec	d_{max}, cm	Δt_L, sec
10	0.262	0.136	0.254	0.057
20	.131	.034	.127	.014
40	.065	.009	.063	.004

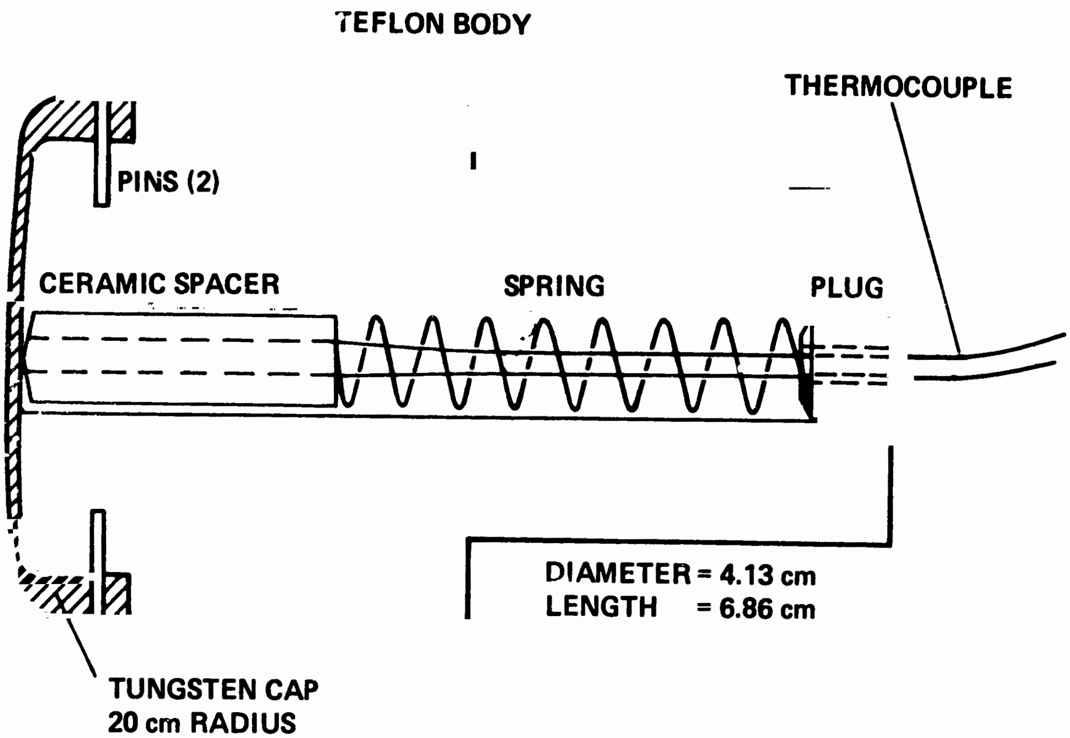

Figure 1.- Tungsten-cap calorimeter probe.

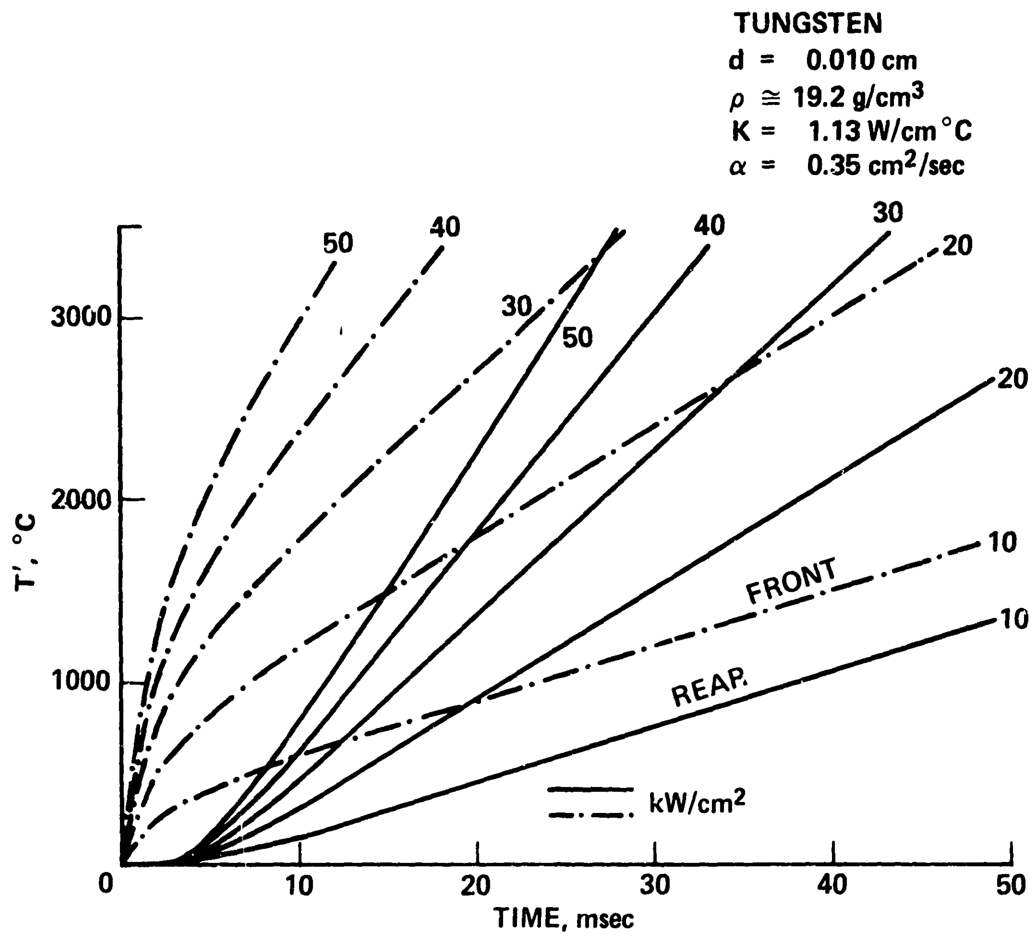

Figure 2.- Calorimeter surface temperature versus absorbed heat flux and exposure time.

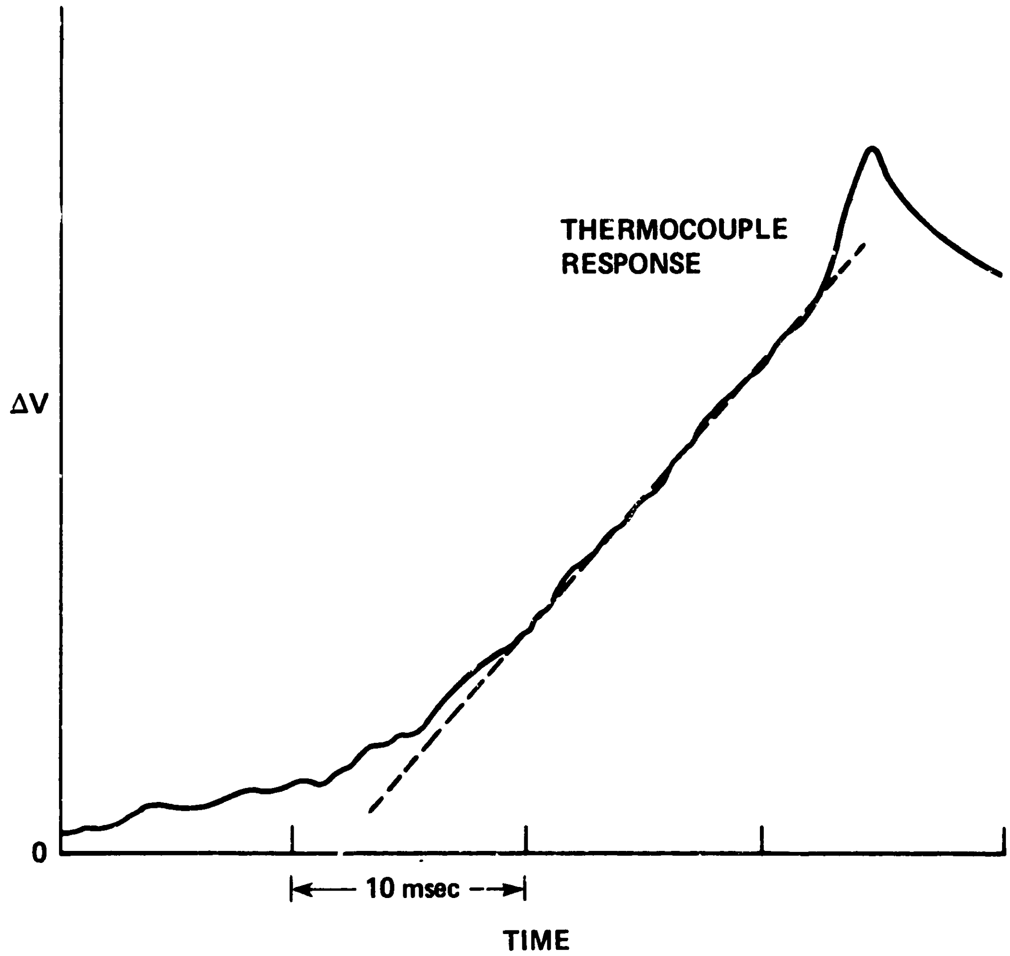

Figure 3.- Tungsten calorimeter arc jet response.